A New State of Beauty and Charm

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The ATLAS Experiment at the Large Hadron Collider has announced* the discovery of a new particle: the $B_c^{\pm}(2S)$. This was the third particle discovered at the LHC, following the Higgs (4 July 2012) and the $\Xi_b(3P)$ (22 June 2012).

The topic of this colloquium is the role of this new particle in our understanding of nature.

**Phys. Rev. Lett. 113, 212004 (2014)*

The $B_c(2S)$ is a system of two heavy quarks---heavier than the ones in protons and neutrons---bound together by the Strong Force.

Although heavy quarks do not feature prominently in daily life, they turn out to be particularly useful in probing certain features of the strong force.

➔so characteristics of the $B_c(2S)$ can illuminate a broader class of questions.

Some background info on quarks and strong interactions…

- The Strong Force holds the nucleus together, overcoming electrostatic repulsion of the constituent protons. Its range is short, just 10^{-15} m, and this sets the radius of a typical nucleus.

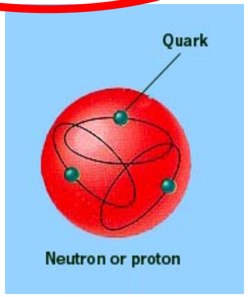
- As is usual in field theory, the force is transmitted through a mediator particle. The mediator of the strong force is the gluon….it "glues" the nucleus together.

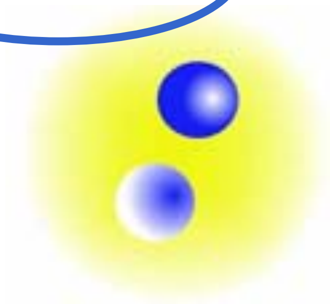
- The nucleus is composed of protons and neutrons, but these are made of quarks, so we can think of the nucleus as a bag of quarks exchanging gluons.

some facts, continued…

- The principal quarks in the proton and neutron are types "up" and "down." These are all that's needed to build the nuclei of normal elements. But there are 4 more types of quarks known to exist, able to be produced in cosmic ray collisions and particle accelerators and surely existing since the early universe.

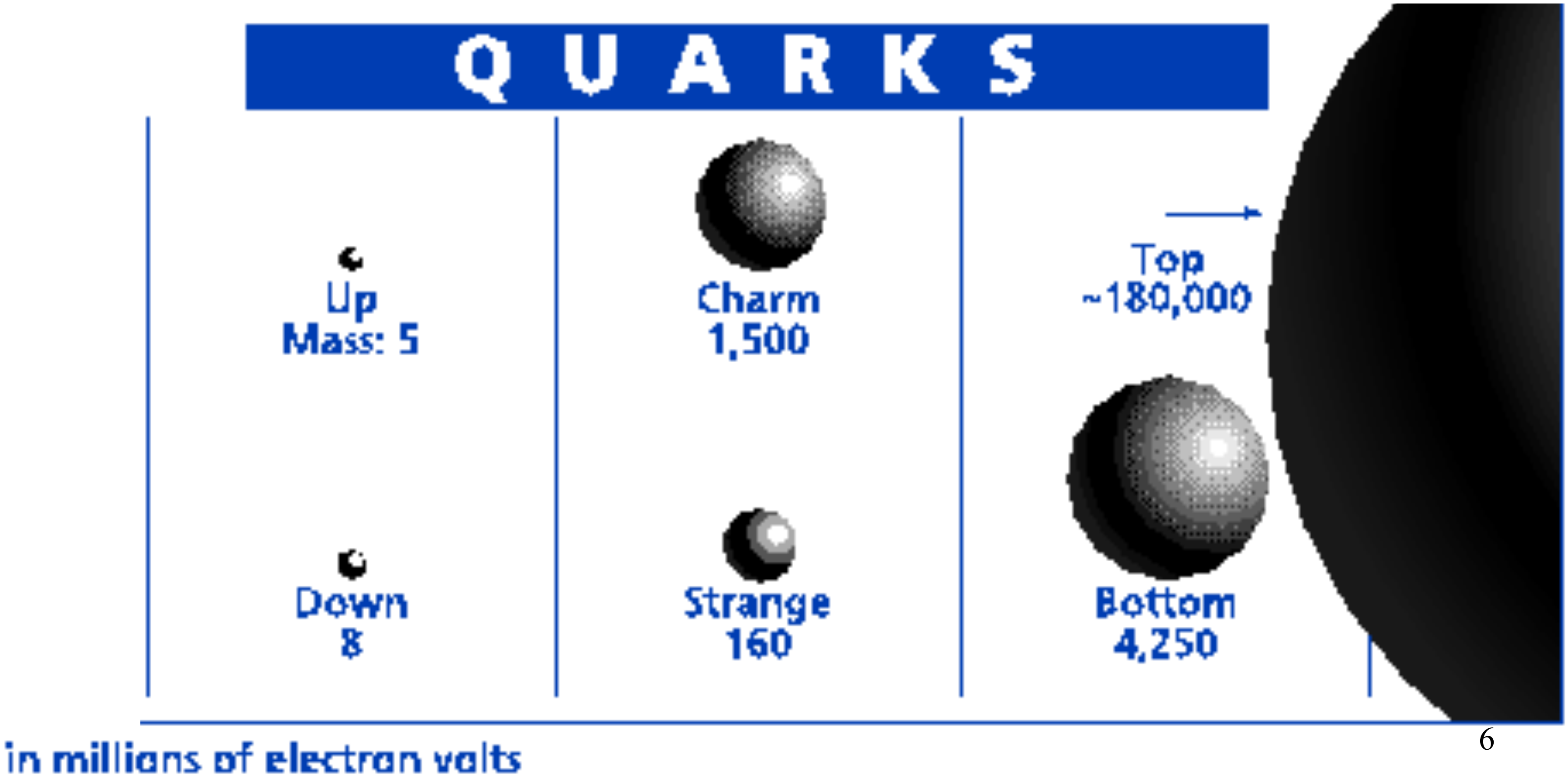
- It seems that quarks only bind in two forms: color-singlet quark-antiquark pairs ("mesons") and 3-quark bundles ("baryons"):





Something puzzling about quarks…

The common ones are light. The less common are 20 to 20000 times heavier (but still dimensionless!) What does this pattern mean? What role do these heavy quarks play in the universe?

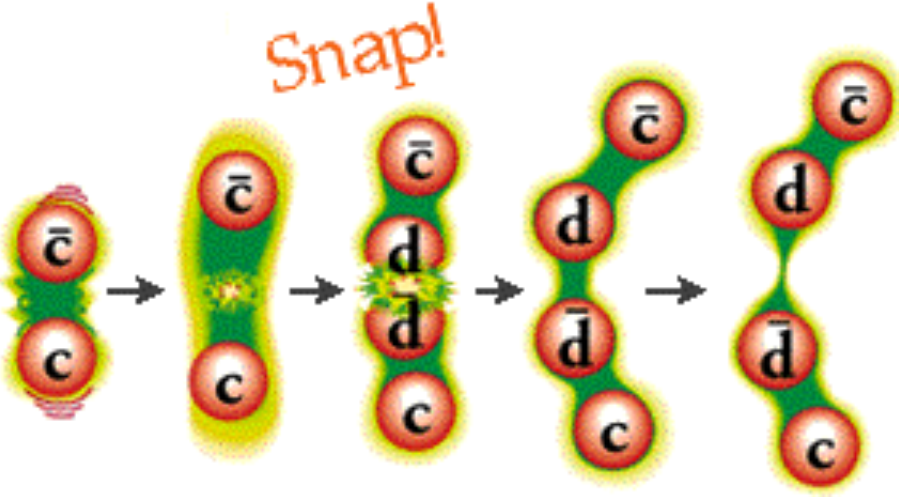


The strong force differs from the electromagnetic and gravitational forces in an important way…

The electrical and gravitational forces get *weaker* as the distance between particles increases:

$$F_{elec} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^2} \quad \text{and} \quad F_{grav} = G\frac{m_1 m_2}{r^2}$$

The strong force gets *stronger* with distance.



This effect leads to *confinement*: "no free quarks." Quarks are permanently confined in bound states.

The underlying cause is an unsolved problem. Proposed mechanisms‡ include an analog to the Meissner effect in which quarks are confined by an electric flux tube in a condensate of magnetic monopoles.

Confinement makes *measurements* challenging!
The fundamental processes that we want to understand take place between individual pointlike partons, but before these reach detectors, they form bound states. Direct measurements of the interacting partons are impossible.

‡A good review: R. Alkofer and J. Greensite, J. Phys. G: Nucl. Part. Phys. 34 (2007) S3-S21.

This makes *theoretical calculations* of strong processes difficult too.

Quantum mechanics often relies on perturbation theory to predict physical observables.

The perturbative series is most likely to be reliable when each term, proportional to the coupling (*strength of the force*) raised to a power determined by the term's place in the series, provides an increasingly smaller correction.

Where the coupling is large, *convergence is suspect.*

This is problematic for descriptions of the process, *"hadronization,"* that binds quarks into observable states.

The theory of the strong force is Quantum Chromodynamics (QCD). Despite calculational challenges, QCD has been very successful. QCD is in many ways modeled on QED, the theory of electromagnetism. However whereas QED has been shown to predict phenomena "to the 11th decimal place," some QCD measurements are precise only to within 10%, and quantifying some theoretical systematics is challenging.* So there's plenty of work for an experimenter to do.

For example, the exact form of the strong potential, the strong analog to

$$V_{elec} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r}$$

is not known.

*J. Pumplin et al., JHEP 0207:012 (2002).

A important test of QCD is its ability to predict the energies of observed bound states.

Where perturbative expansion is problematic, several approaches have been taken to this problem…

- **Lattice calculations** ---introduction of a cutoff to control divergences when two fields are evaluated at the same point. Could be a minimum distance between 2 local fields: spacetime becomes discrete. Special problem for bound states of heavy (large mass m) quarks: they move slowly---small velocity v. Predictions are limited by computational power associated with lattice extent (large compared to $1/mv^2$) and granularity (small compared to $1/m$).

- One can try **Effective Field Theory** (EFT) instead...a quantum field theory in which different scales are factorized, leaving adequate degrees of freedom to describe phenomena in a specific range. Typically an EFT has *a potential* which encodes the effect of degrees of freedom that have been integrated out from full QCD.

These potentials can be classified as "non-QCD- like" (phenomenological) and "QCD-inspired.”

At short distances, lowest order perturbation theory gives a Coulomb-like potential for one-gluon exchange

$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r}$$

but *this does not include confinement. Another term must be added…*

Experimentally, $q\bar{q}$ production typically occurs at an energy scale 1 GeV (typical hadron mass) at a separation of 1 fm (typical hadron size). *So at long distances,* one-gluon exchange can be replaced by bunched "color flux tubes" with linear energy density σ:

$$V(r) = \sigma \cdot r$$

This gives the "Cornell potential":

$$\sigma \equiv \frac{\Delta E}{\Delta r} \cong 1\frac{\text{GeV}}{\text{fm}} \cong 0.18\,\text{GeV}^2$$

Spin-*independent* features of $q\bar{q}$ spectroscopy have been shown to be described by this form.

E. Eichten et al., Phys. Rev. D 17, 3090 (1978).

Other phenomenological spin-independent potentials tuned to match charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$) spectra include the

- Logarithmic potential,
  - *Phys. Lett. B 71, 153 (1977)*

$$V(r) = A\log(r/r_0)$$

- Richardson potential,
  - *Phys. Lett. B 82, 272 (1979)*

$$V(q^2) = -\frac{4}{3}\frac{12\pi}{33-2n_f}\frac{1}{q^2}\frac{1}{\ln(1+q^2/\Lambda^2)}$$

- Buchmüller-Tye potential,

$$V(r<0.01\,fm) = -\frac{16\pi}{25}\frac{1}{r\ln(1/\Lambda^2 r^2)}\left[1+\left(2\gamma_E+\frac{53}{75}\right)\frac{1}{\ln(1/\Lambda^2 r^2)}-\frac{462}{625}\frac{\ln\ln(1/\Lambda^2 r^2)}{\ln(1/\Lambda^2 r^2)}\right]$$

  - *Phys. Rev. D 24, 132 (1981)*

- Martin potential,
  - *Phys. Lett. B 93, 338 (1980).*

$$V(r) = A(r/r_0)^{\alpha}$$

- The QCD-inspired spin-dependent[‡] and velocity-dependent potentials have been written down, for example:

$$V_{sd}=\left(\frac{\vec{S}_1\cdot\vec{L}_1}{4m_1^2}-\frac{\vec{S}_2\cdot\vec{L}_2}{4m_2^2}\right)\left[\frac{1}{R}\frac{d\varepsilon(R)}{dR}+\frac{2}{R}\frac{dV_1(R)}{dR}\right]+\left(\frac{\vec{S}_2\cdot\vec{L}_1}{2m_1m_2}-\frac{\vec{S}_1\cdot\vec{L}_2}{2m_1m_2}\right)\frac{1}{R}\frac{dV_2(R)}{dR}$$
$$+\frac{1}{6m_1m_2}\vec{S}_1\cdot\vec{S}_2\vec{\nabla}^2V_2(R)+\frac{1}{12m_1m_2}(3\vec{S}_1\cdot\hat{R}\vec{S}_2\cdot\hat{R}-\vec{S}_1\cdot\vec{S}_2)V_3(R)$$

- and even further refinements of this are available. [§]

‡ *E. Eichten and F. Feinberg, Phys. Rev. D 23, v.11, 2724 (1981).*

§ *A. Pineda and A. Vairo, Phys. Rev. D 63, 054007 (2001) and Phys. Rev. D 039902 (2001).*

Each proposed potential function leads to a hypothesized spectrum. For example, from Godfrey and Isgur, Phys. Rev. D 32, 189 (1986), predicted mass of bottom-charm bound states:

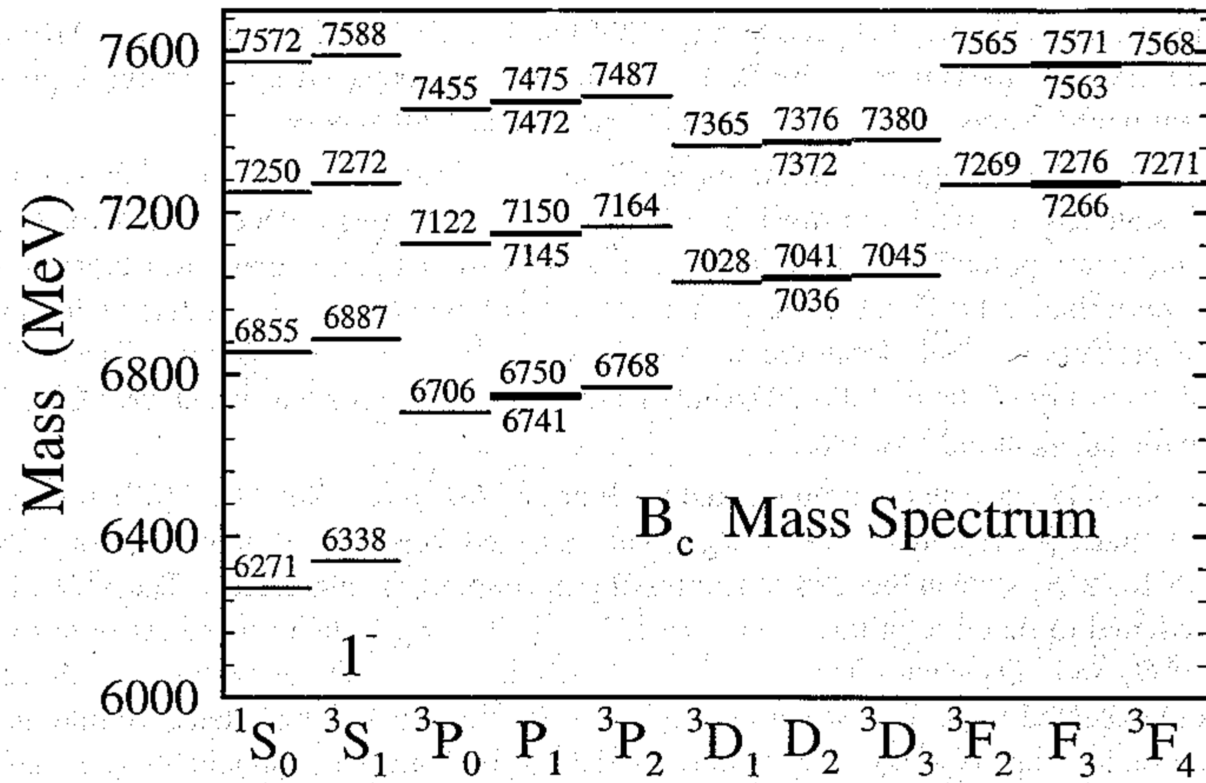


Fig. 3.9: B_c spectrum.

Another approach to QCD is through lattice calculations.

Here*, the first lattice prediction of radially excited and P-wave B_c states.

*R.J. Dowdall, et al., HPQCD Collaboration, Phys. Rev. D 86, 094510 (2012).

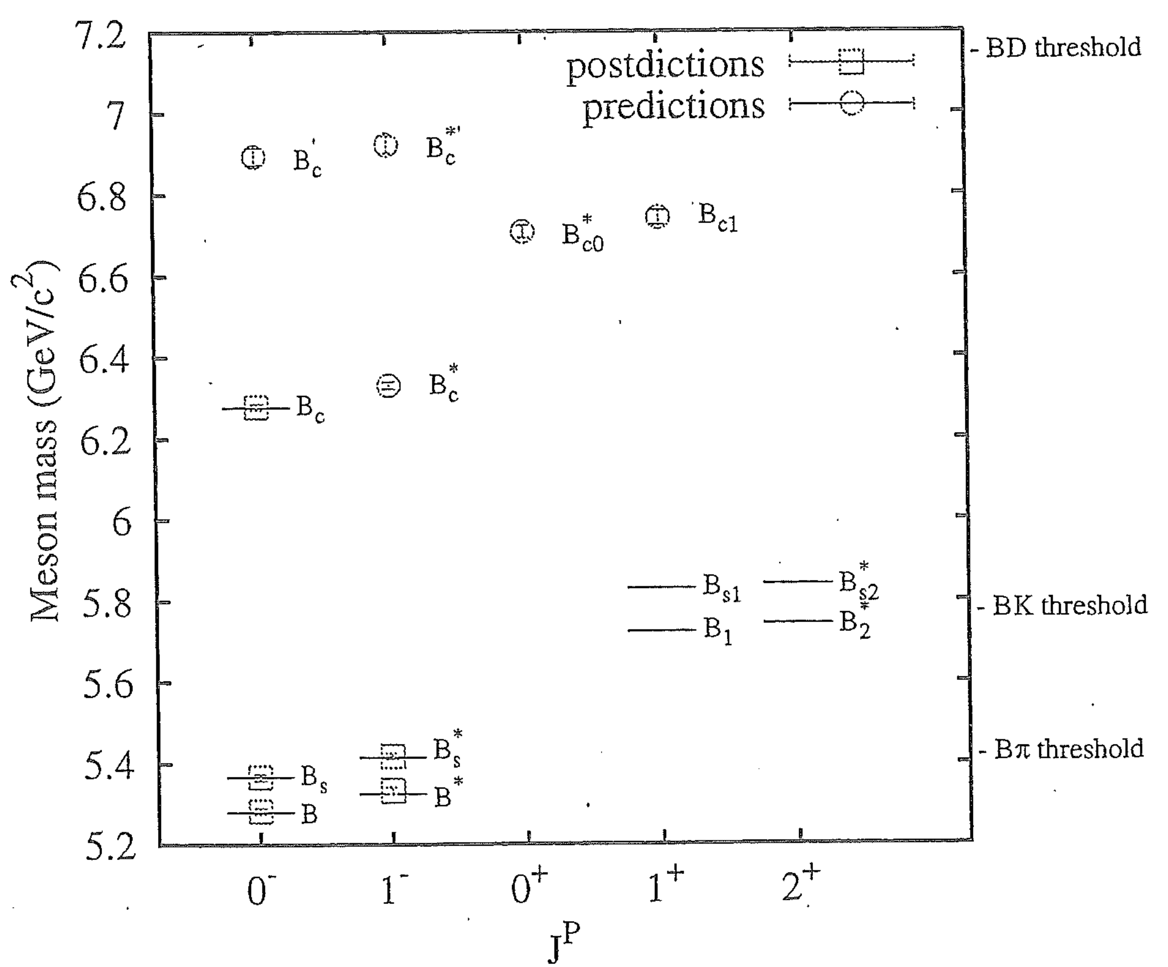
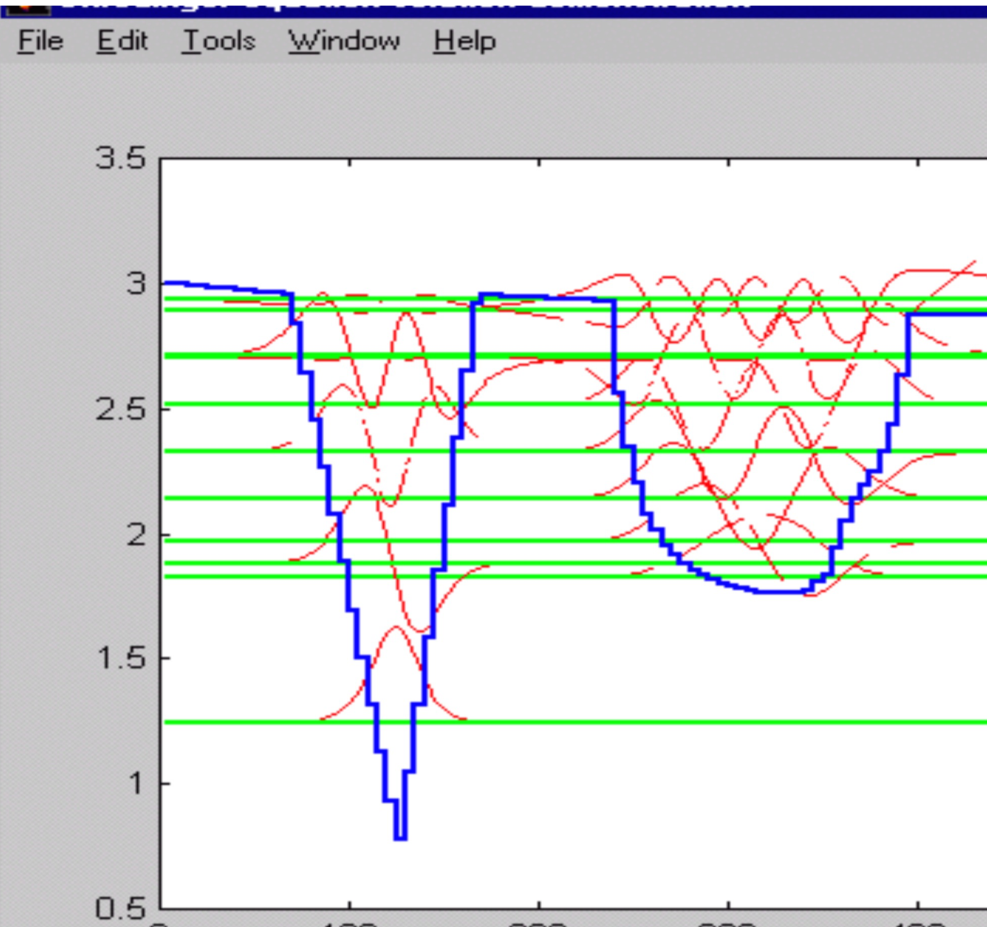


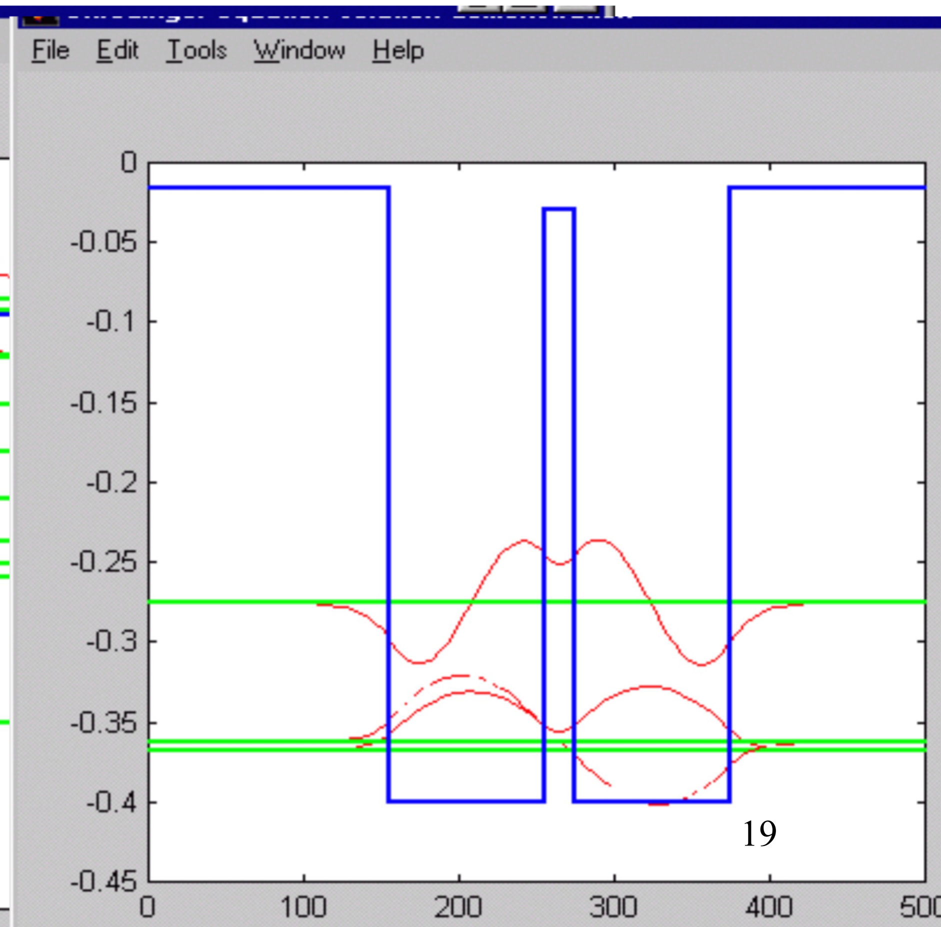
FIG. 17. The spectrum of gold-plated B, B_s and B_c meson states from this calculation, compared to experiment where results exist. Predictions are marked with open red circles. None of the meson masses included here were used to tune parameters of the action so all the masses are parameter-free results from lattice QCD.

So a reasonable experimental goal is to map the strong potential as predicted by analytical or lattice models.

We know that the detailed shape of a potential determines the energies at which its states are bound.

Compare:





Heavy quark bound states are key to elucidating the strong potential.

Bound states of light quarks can be modeled by a perturbed Coulombic spectrum, but this isn't complete. The light quark states probe the short range of the potential, while heavier states are needed to probe the long.

The spectrum of $c\bar{c}$ and $b\bar{b}$ states is known and is not purely Coulombic.

The ideal laboratory for mapping the strong potential...the B_c system: bound states of one charm and one anti-bottom quark (or their antiparticles):

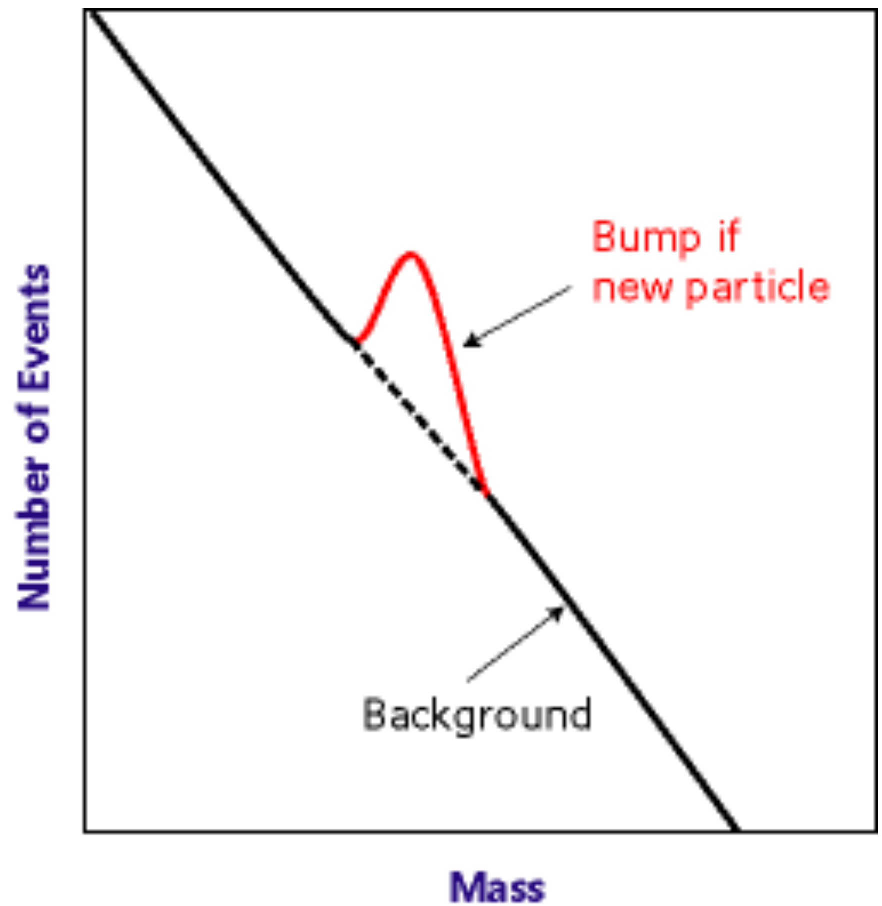
The B_c is a good laboratory for comparing data to theory on the shape of the strong potential because:

- modeling the binding of a two-body ($q\bar{q}$) system is easier than modelling three bodies (qqq)---so start with a meson.
- the heavier the better, to suppress relativistic effects---but $t\bar{t}$ cannot form, because top quarks decay before binding.
- But the *main reason** uses the fact that while particle decays can be mediated by any of the forces, *each force introduces its own characteristic time to the process*:

Weak decays typically require	10^{-12} sec
Electromagnetic:	10^{-20} sec
Strong:	10^{-23} sec

*C. Quigg, FERMILAB-CONF-93/257-T

- If we used $b\bar{b}$ or $c\bar{c}$ mesons, they would bind but decay rapidly ($\Delta t \sim 10^{-20}$-10^{-23} seconds) by annihilation through the electromagnetic interaction.
- Due to the uncertainty principle, $\Delta E \Delta t \geq \hbar / 2$, small Δt means $b\bar{b}$ or $c\bar{c}$ resonance widths ΔE are large.
- But the wider a peak, the poorer the resolution on its mass, and the harder to distinguish it from background



- We want a narrow resonance for precision measurement of the mass. We want a resonance that decays weakly.
- B_c cannot decay through the strong and electromagnetic forces because those conserve quark type ("flavor") which prevents the two flavors (b and c) of the B_c from annihilating. B_c must decay weakly.

B_c must be narrow---providing a precise mass value.

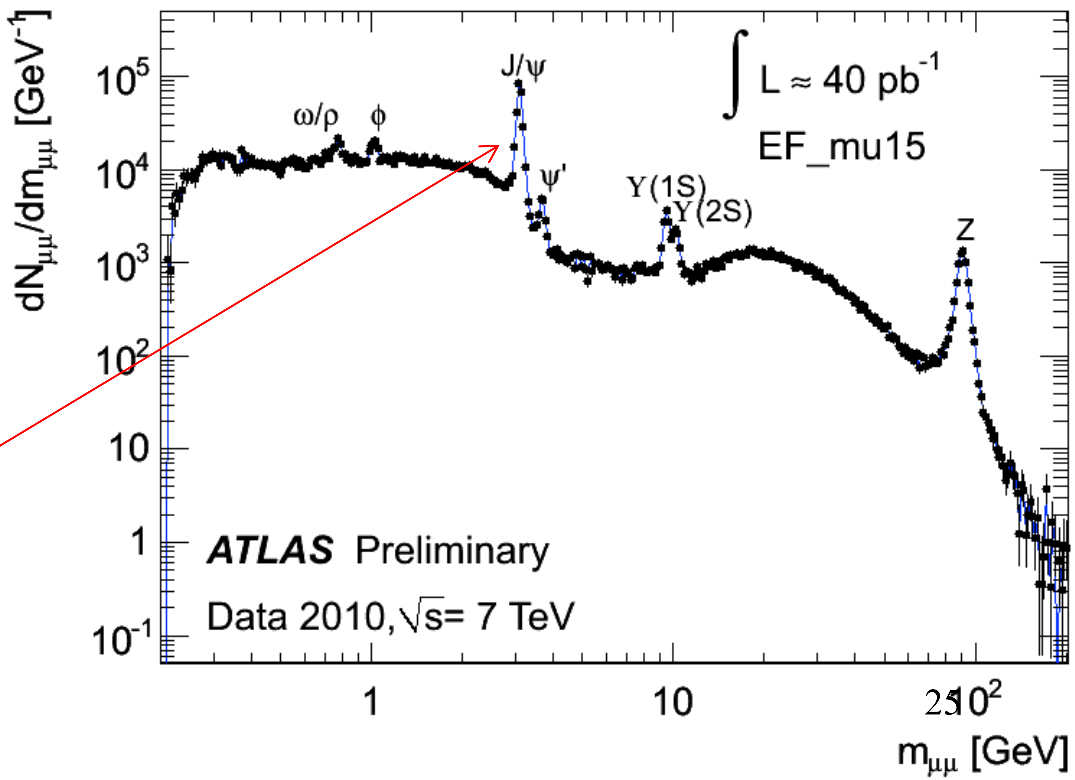
The B_c can decay to various final states, and we choose one:

$$B_c \rightarrow J/\psi\pi$$

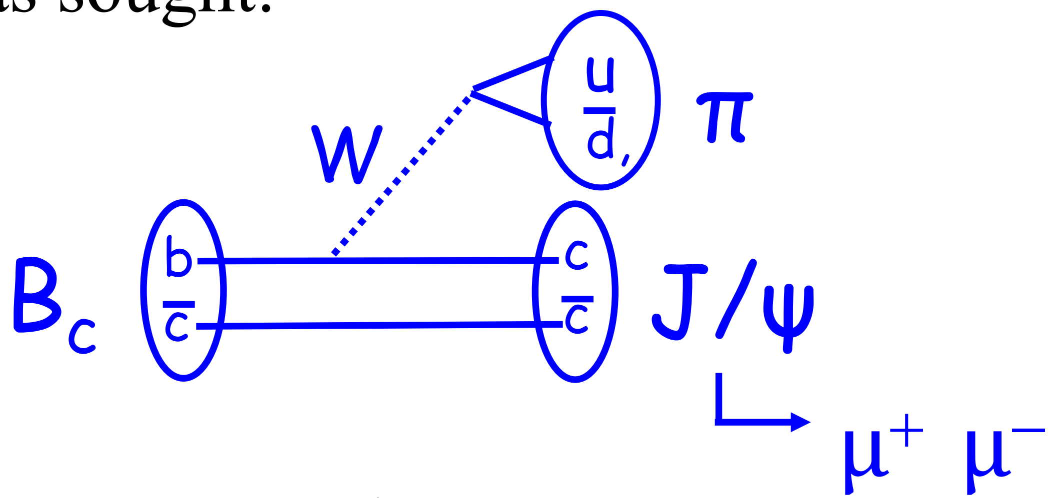
in which all of the final particles can be observed (*no invisible neutrinos*). This J/ψ has a clean decay signature of its own:

$$J/\psi \rightarrow \mu^+\mu^-$$

Clean because muons, and only muons, are detected efficiently by *muon detectors* that surround most contemporary collider experiments, and the J/ψ has a very narrow peak.



Here's what was sought:



The B_c has a high mass...about **6 GeV**:

6 times heavier than the proton...

so it and its family can only be produced at the highest energy colliders.

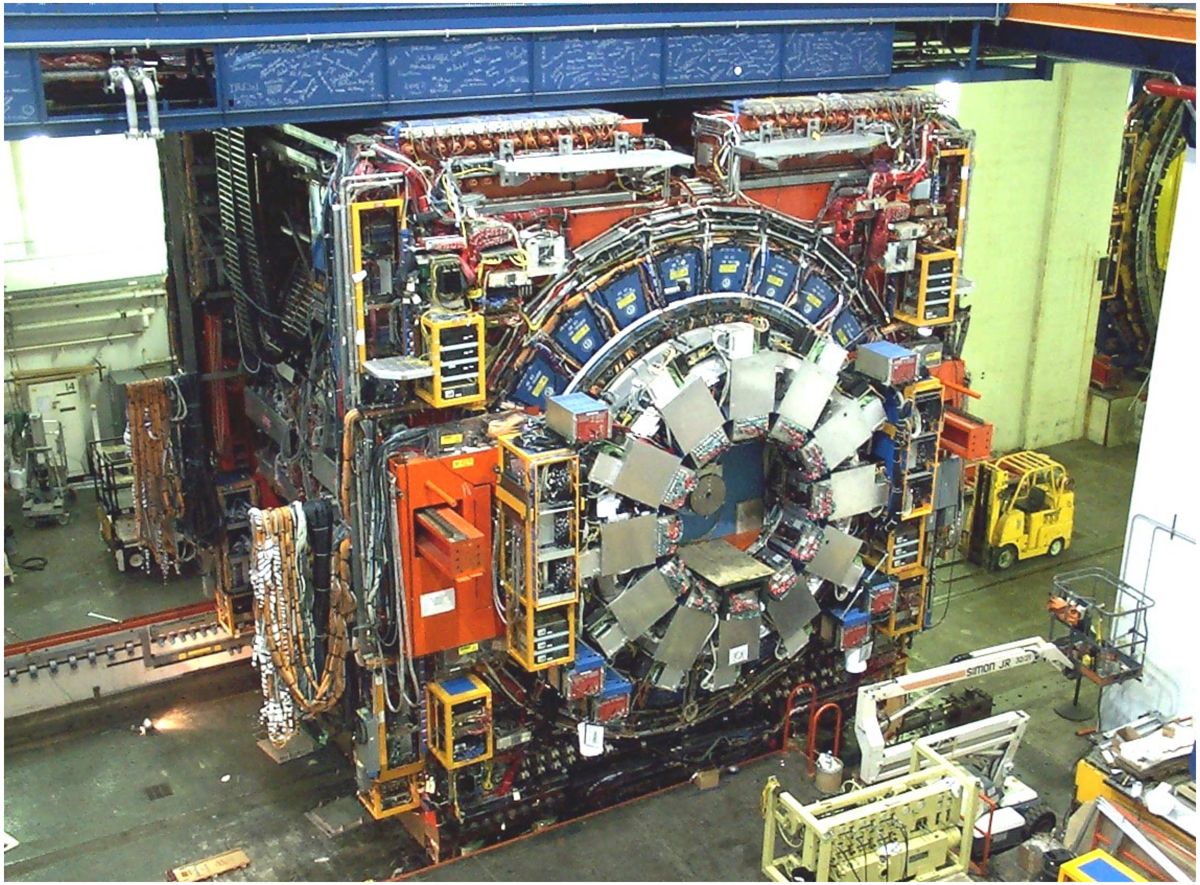
Precision measurements of it and its excited states should provide a map of the strong potential and targets for comparisons to the lattice calculations.

The ground state of the B_c system was discovered* in 1998 at the Fermilab Tevatron Collider…

on the basis of 20 events (occurrences) extracted by the CDF Experiment from almost a decade's worth of data. But this first observation used a decay channel involving a neutrino, that's $B_c^{\pm} \to J/\psi \ell^{\pm} \nu_{\ell}$, so a price was paid in precision.

*F. Abe et al., PRL 81, 2432 (1998).

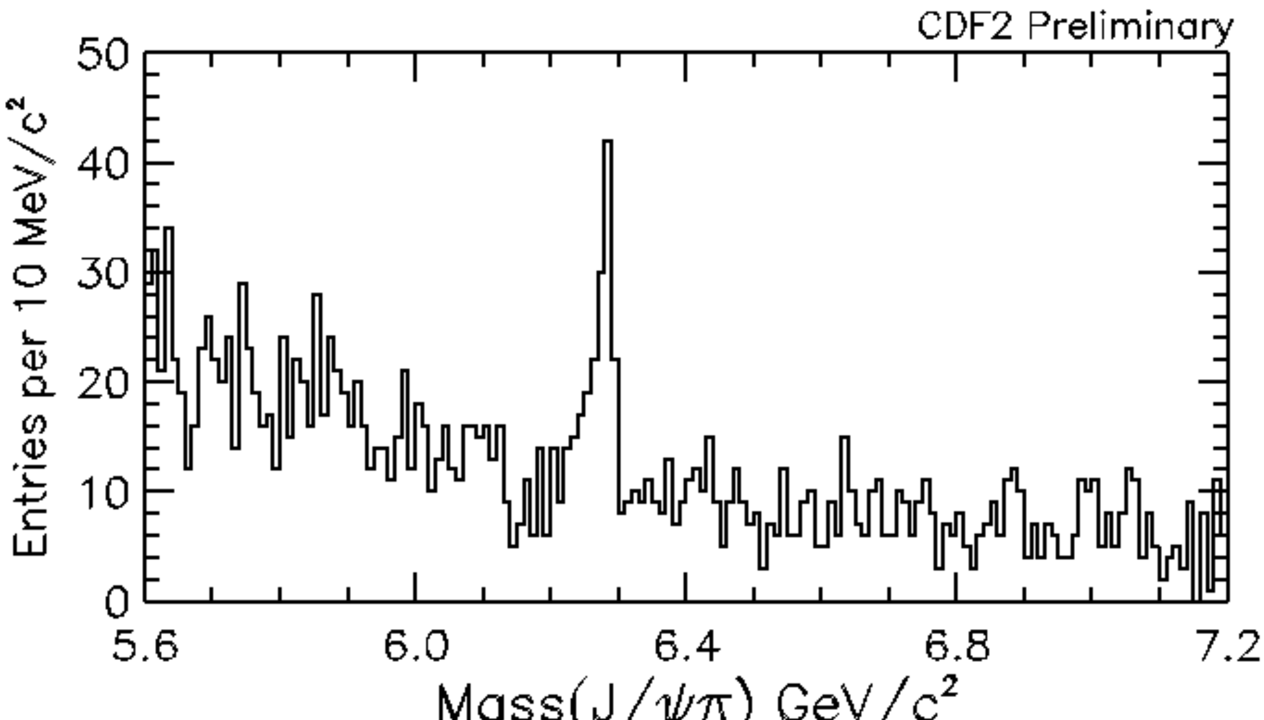
The *precision* mass measurement* occurred in 2005,



when the B_c was for the first time fully reconstructed through $B_c \to J/\psi\pi,\ J/\psi \to \mu^+\mu^-$. In 18 years' worth of data (over half a billion events recorded) there were 14.6 ± 4.6 events of this type were found. *A. Abulencia et al., PRL 96, 082002 (2006).

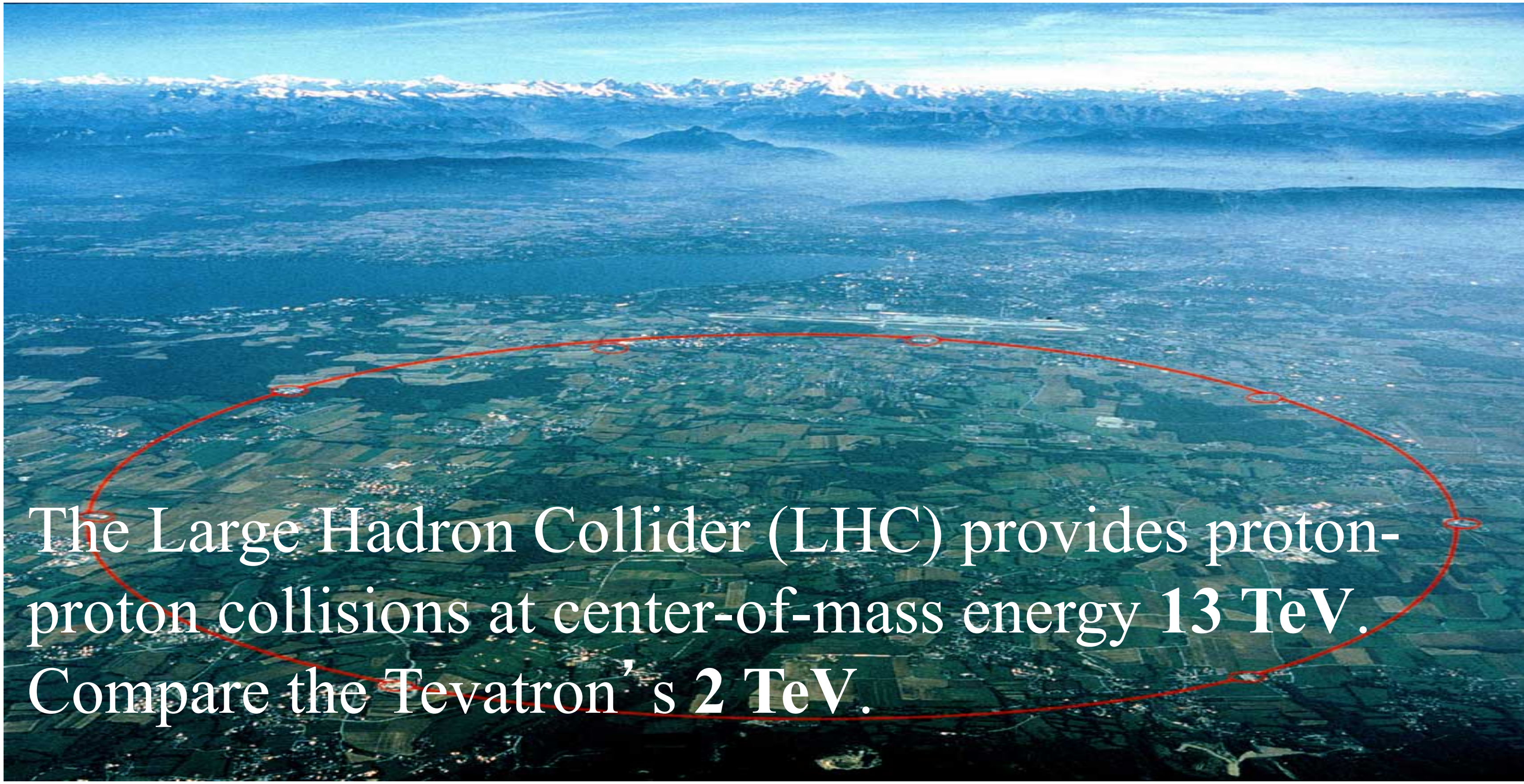
In May 2008 this was updated* with 108 more events from another near-decade of collisions. *Collecting enough data to find this 'needle in a haystack' required* ***20 years*** *of Tevatron collider operation.*

But the state is indeed narrow, as required:



*T. Aaltonen et al., PRL 100, 182002 (2008).

Discovery and precision measurements of the excited states require a higher rate of events.



The Large Hadron Collider (LHC) provides proton-proton collisions at center-of-mass energy **13 TeV**. Compare the Tevatron's **2 TeV**.

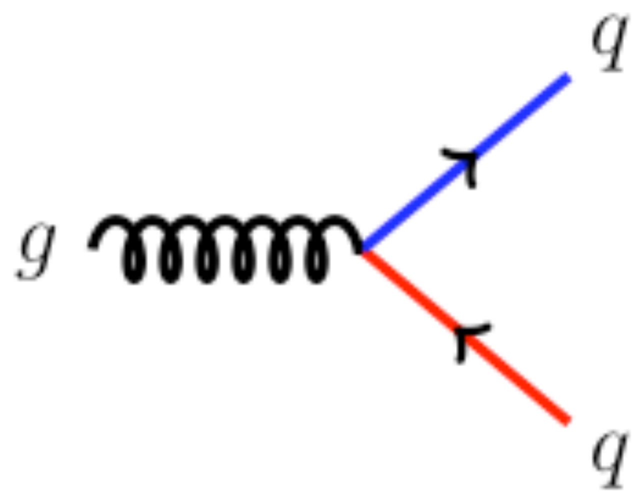
The LHC produces **collisions 30 times faster** than the Tevatron by a combination of more protons and shorter gaps between bunches.

$\text{Lumi}_{\text{LHC}}/\text{Lumi}_{\text{Tev}}=1.2\times10^{34}/4\times10^{32}$

The protons that collide at the LHC are not simple 3-quark bags, but complex systems of valence quarks, sea quarks, and the gluon cloud that binds them.

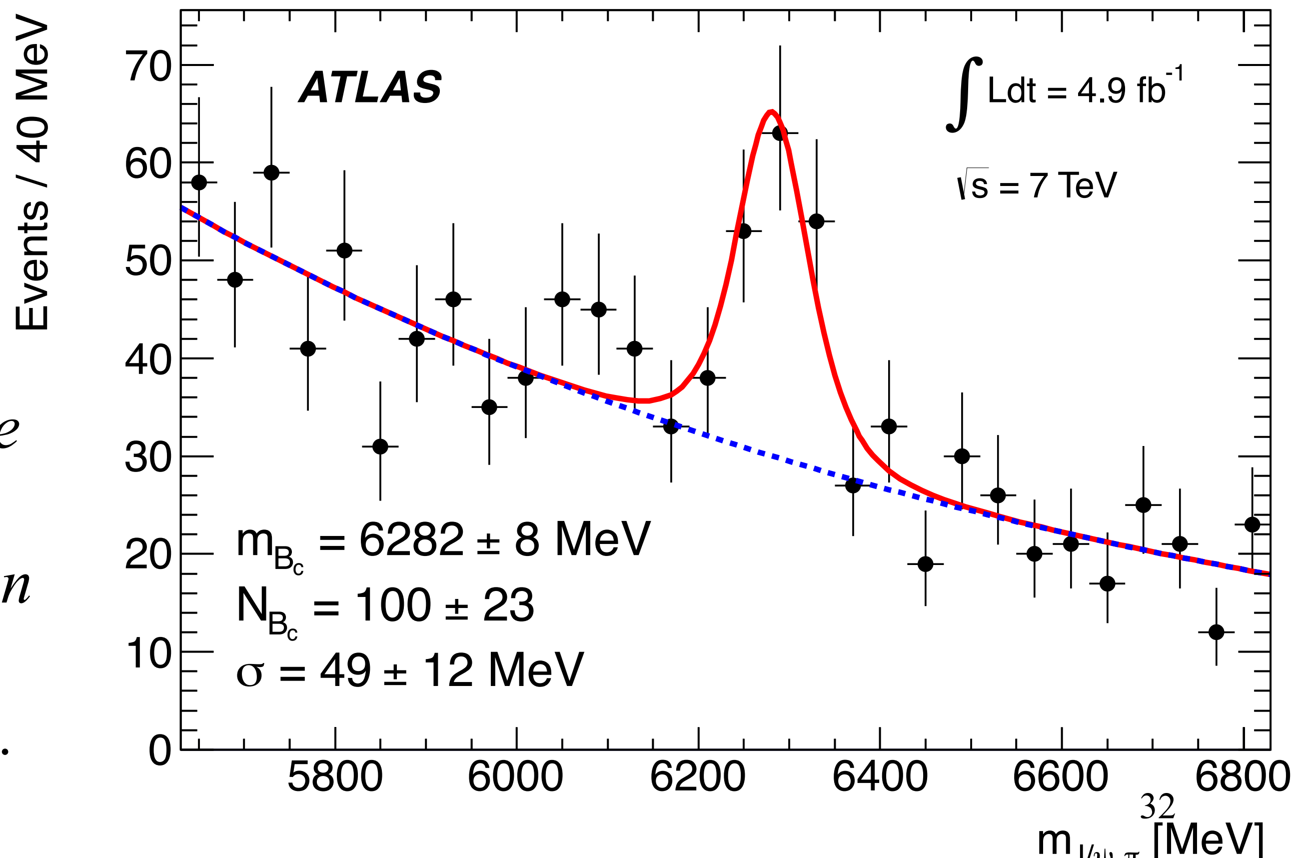
80% of the events at the LHC are gluon-gluon collisions.

Production of heavy states increases with energy as gluons become increasingly likely to split to heavy quarks, including b and c.

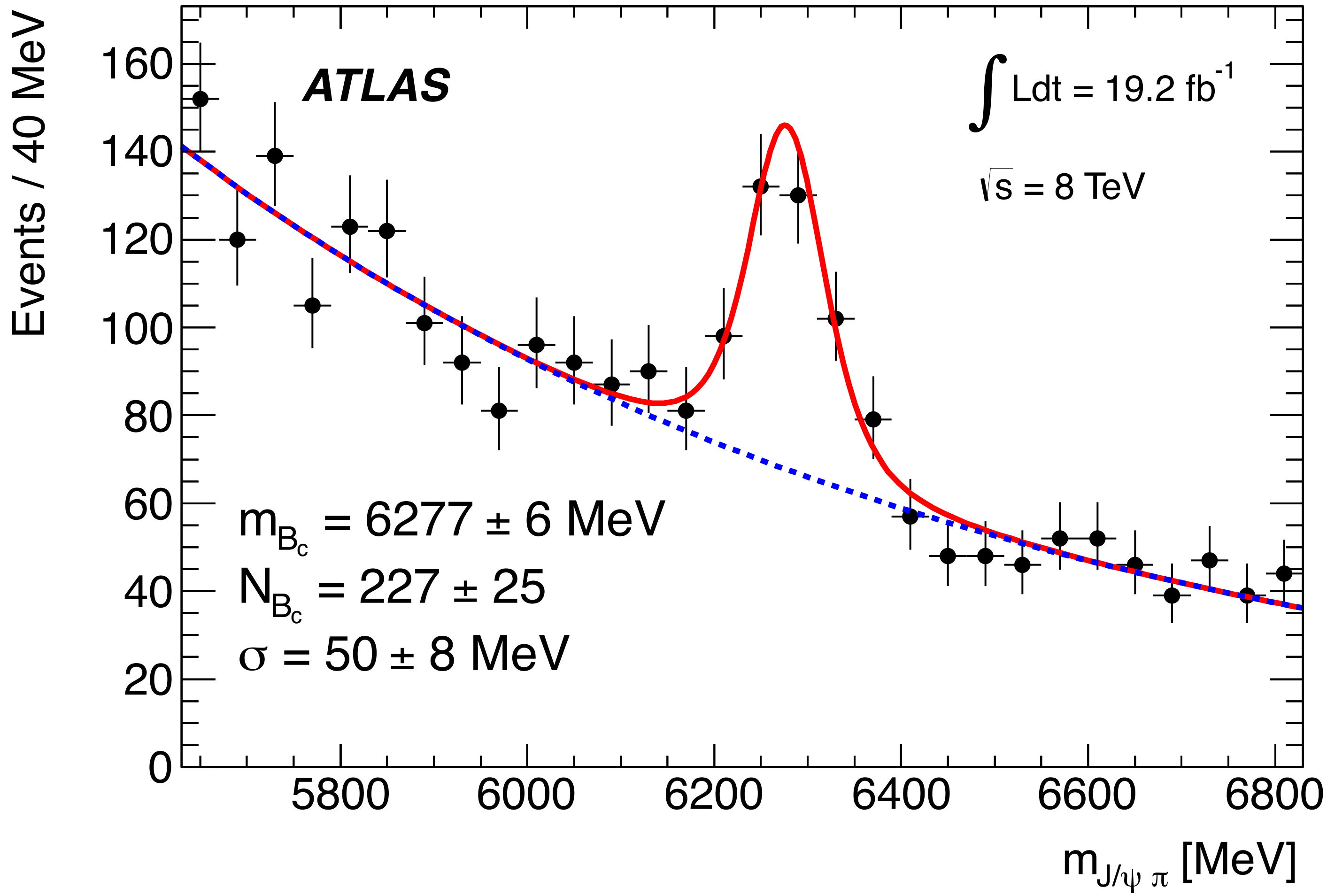


In the year 2011 alone, the experiments at CERN collected about 10 times as many collisions as the 24-year Tevatron dataset, and the B_c ground state was observed in over 800 events. It's now well-established.

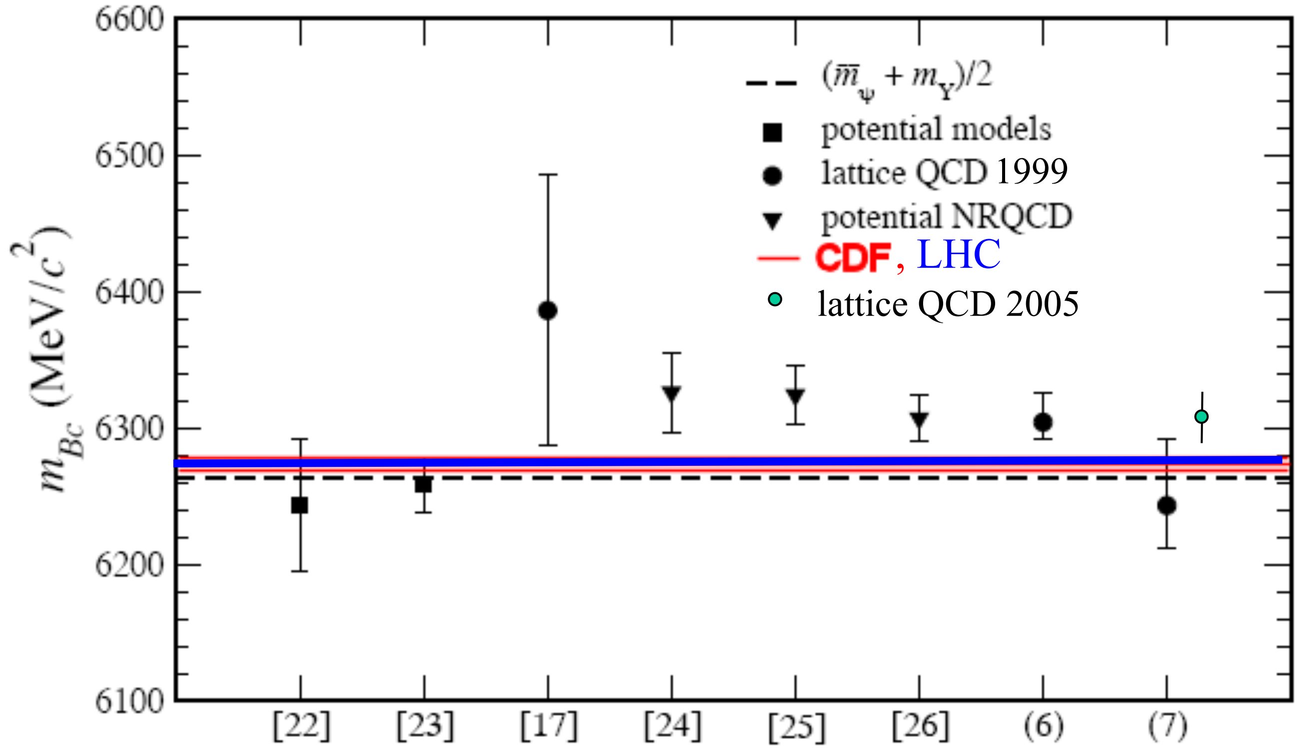
100 B_c ground state events in in 2011, from the dissertation of UNM graduate student Rui Wang...



In 2012, 200 more B_c ground state events were reconstructed by ATLAS as the collider energy increased from 7 to 8 TeV (production cross section grew by 3%), and the data collected increased five-fold:



How does this compare with theory?



It challenges all of them!

mass $(B_c)_{CDF} = 6275.6 \pm 2.9 \pm 2.5$ MeV/c^2

mass $(B_c)_{LHCb} = 6276.28 \pm 1.44 \pm 0.36$ MeV/c^2

I.F. Allison et al., PRL 94, 172001 (2005)

This precision measurement of the B_c mass provides the baseline against which models of the strong potential can be calibrated.

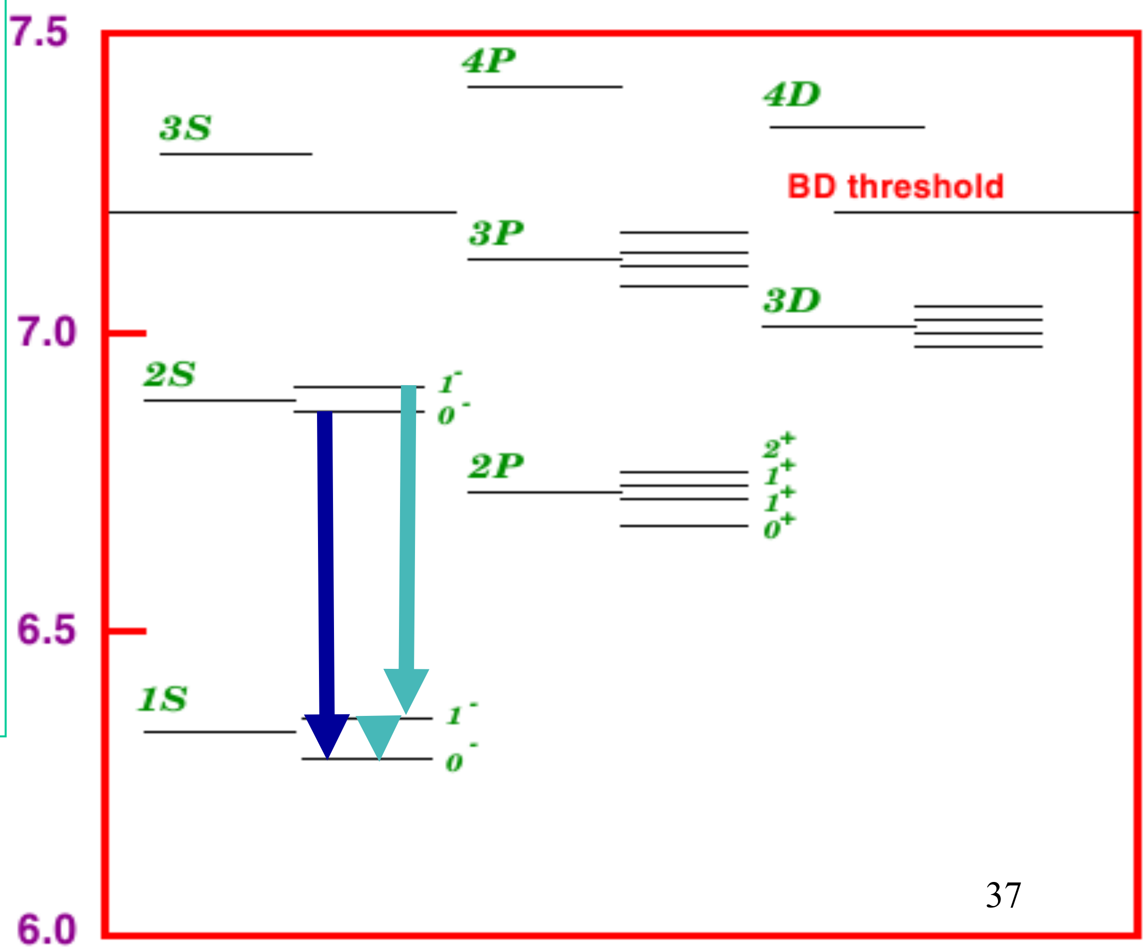
But to map the shape of the potential, we need to know what other stationary states it supports, and we need precision mass measurements of them.

So we need the excited B_c states too.

We search for them using ATLAS at the LHC: the largest ‘camera’ ever built.

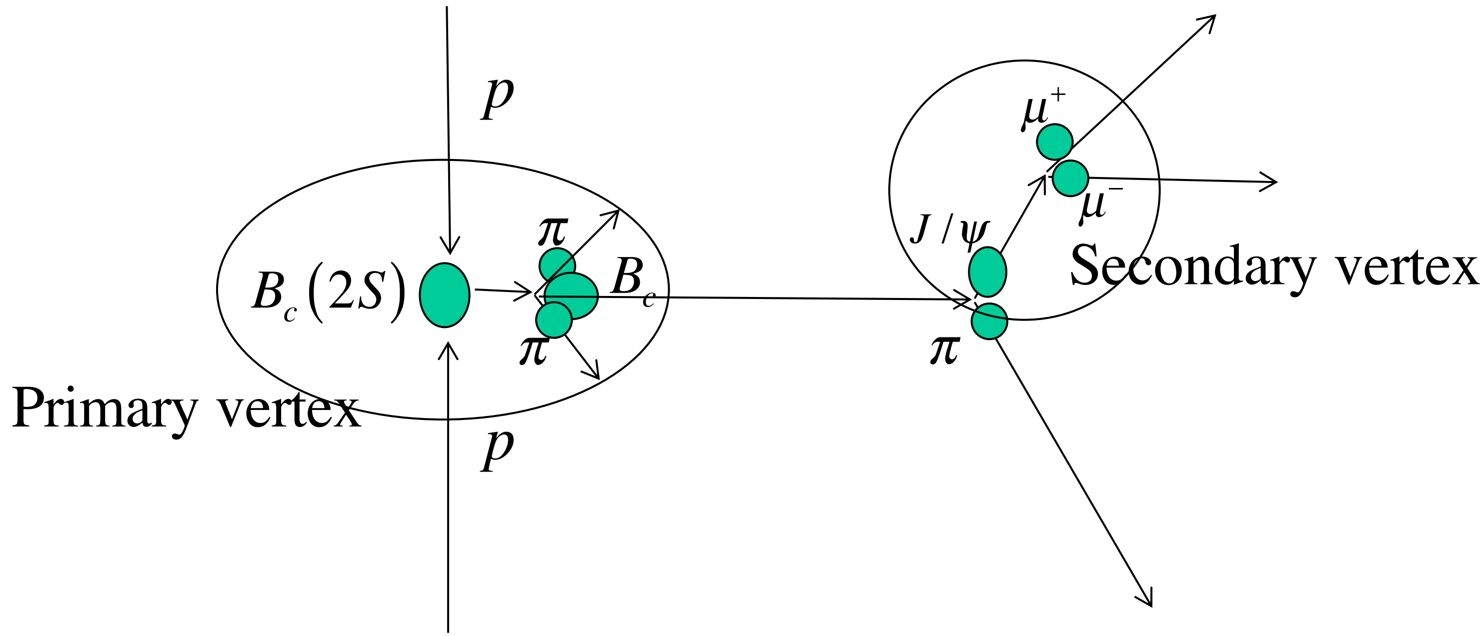
We began our reconstruction of the excited states with the B_c(2S), through its channel $B_c(2S) \to B_c\pi\pi$. *Predictions of its mass range over 6835-6917 MeV.**

Both the 1S and 2S states have pseudoscalar 0^- and vector 1^- spin states, expected to be split by 20-50 MeV. Transitions between these hyperfine states will produce soft photons unobserved by ATLAS, so we do not attempt to resolve them.

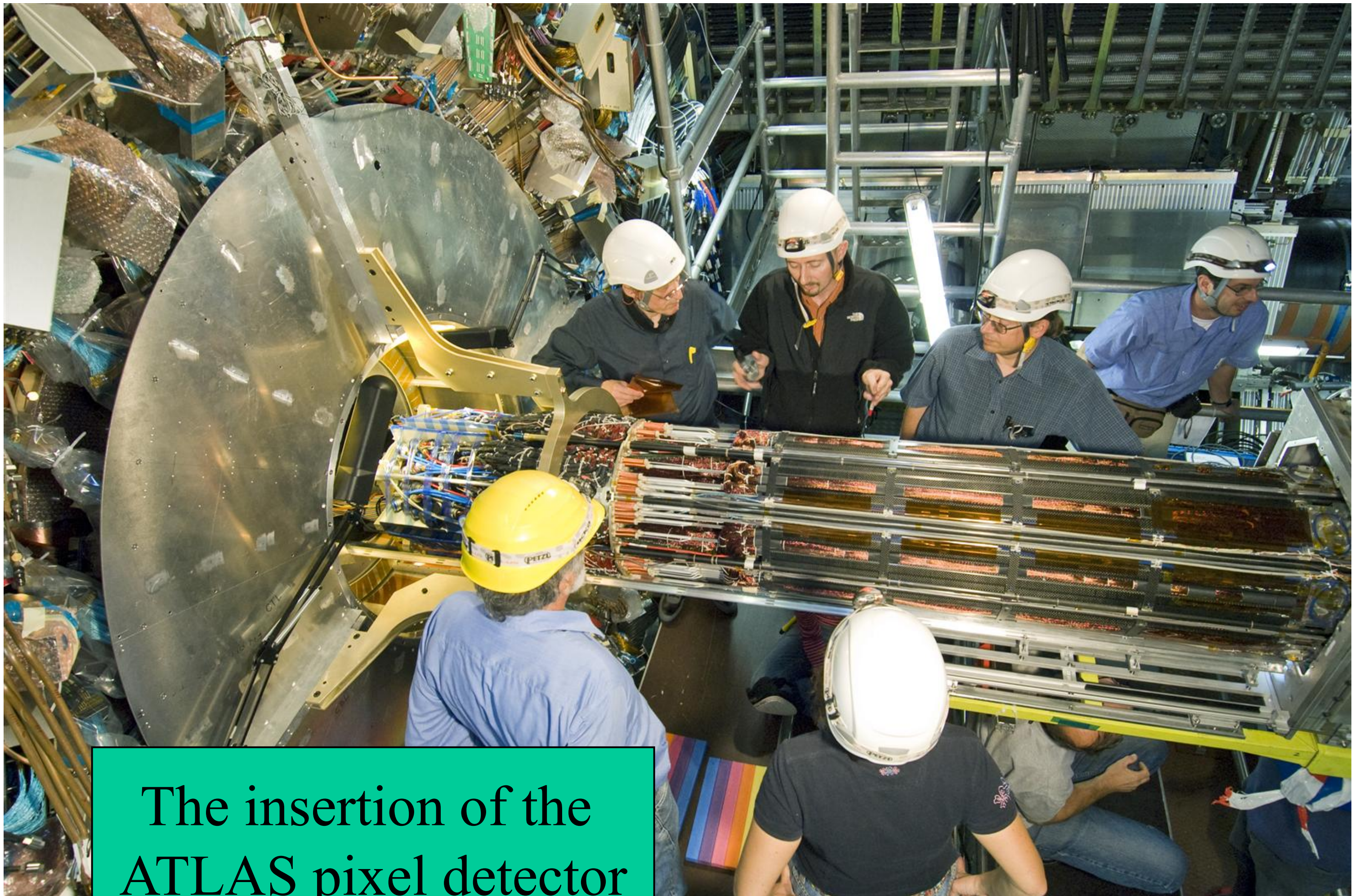


*A list of theoretical references is at the end of the talk.

The critical step in reconstructing the $B_c(2S)$ final state is recognizing the fact that the J/ψ is produced at a different vertex than the point of the primary collision. *The open circles here represent schematically the detector's position resolution:*



That distance between the primary and secondary vertices is resolved in the Pixel Detector at the heart of ATLAS.



The insertion of the ATLAS pixel detector

ATLAS pixel sensors were designed and tested by UNM.

Logical sequence of the search for $B_c(2S)$:

- Beams cross in ATLAS every 25 ns (40 MHz), and about 19 collisions occur in each crossing. We can't examine every event, so we use a trigger to select the most likely ones....Trigger on 2 oppositely-charged muons observed in the detector "barrel" with transverse momenta $p_T > 6$ GeV (muon 1) and 4 GeV (muon 2), reconstructing to a common vertex and an invariant mass consistent with the 3.0969 GeV J/ψ (mass window 2.5 – 4.3 GeV).
- Combine these J/ψ candidates with one pion originating at the same vertex, to form B_c candidates.
- Require B_c decay vertex be displaced from primary (collision) vertex.
- Combine B_c with 2 pions originating at same (primary collision) vertex to form $B_c(2S)$ candidates.

- Histogram mass difference Q = m($B_c\pi\pi$) - m(B_c) - 2m(π), which largely cancels uncertainty on the B_c mass.
- A signal is found in the 2011 (7 TeV, 4.9 fb^{-1} integrated luminosity) data; confirmed in the 2012 (8 TeV, 19.2 fb^{-1}).
- Background to this signal includes the following (ATLAS does not have particle ID):

$$B_c^+ \to J/\psi K^+ \ (K \text{ misidentified as } \pi)$$

$$B_c^+ \to J/\psi \rho^+, \ \rho^+ \to \pi^0 \pi^+ \ (\pi^0 \text{ missed})$$

$$B_c^+ \to J/\psi \mu^+ \nu \ (\nu \text{ unobserved and } \mu \text{ misidentified as } \pi)$$

$$B_c^+ \to J/\psi \pi^0 \pi^+ \ (\pi^0 \text{ missed})$$

$$B_c^+ \to J/\psi \pi^+ \pi^- \pi^+ \ (\pi^+ \pi^- \text{ missed})$$

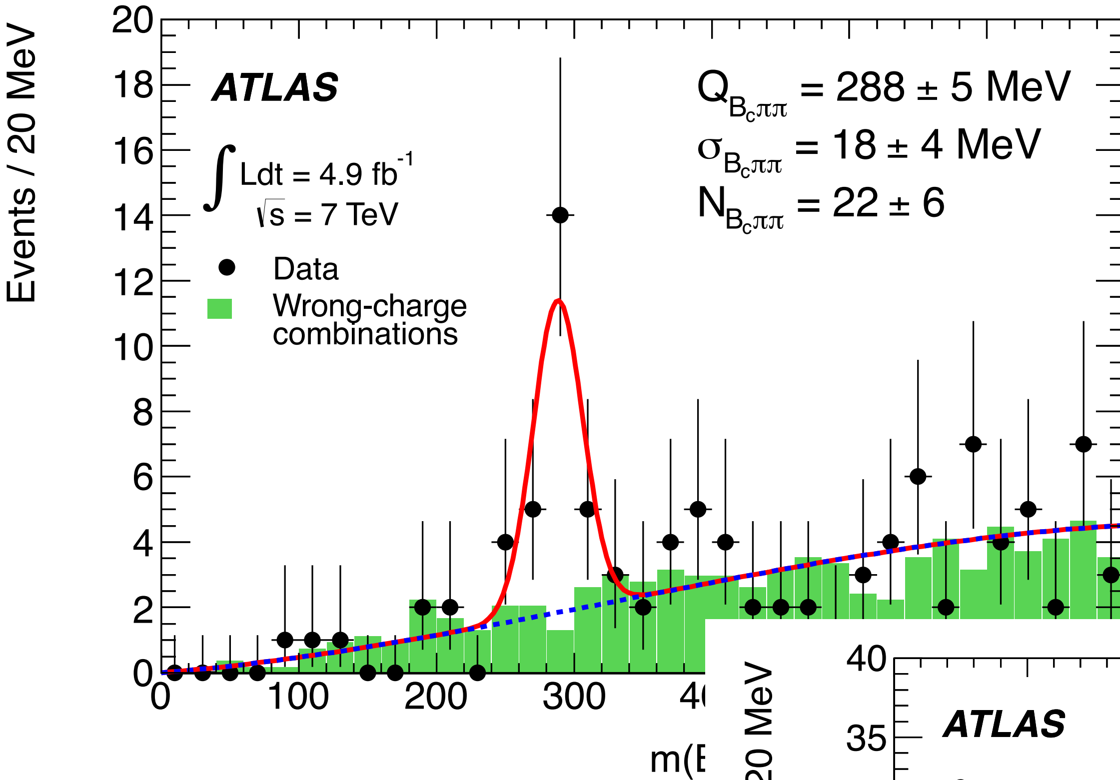
$$pp \to J/\psi X$$

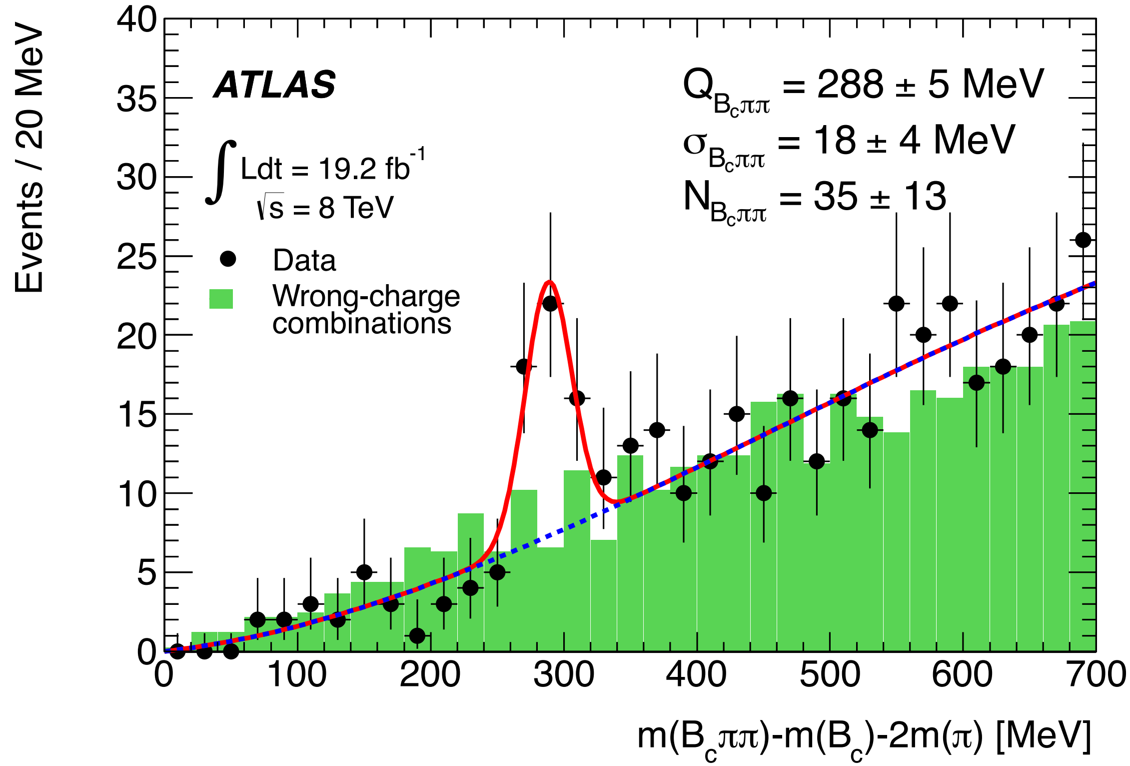
$$pp \to b\bar{b} \to J/\psi X$$

- Model all the backgrounds with Pythia Monte Carlo (MC) , including a dedicated extension PythiaBc written by UNM postdoc Konstantin Toms to model B_c production. Data selection parameters are optimized separately for 7 TeV and 8 TeV because of different pile-up conditions.
- Optimize the J/ψ selection, based on quality of vertex reconstruction, and accounting for different resolutions on the J/ψ mass for muons observed in different regions of the detector.
- Optimize B_c Signal/√(Signal+Background) based on:
  - daughter pion p_T
  - number of measurements in silicon detector
  - significance of separation between vertices
  - quality (χ^2/DOF) of vertex reconstruction
  - B_c p_T

- Apply an extended unbinned maximium likelihood fit to the B_c mass distribution. Resulting mass is consistent with the world average.
- Retain the B_c candidates within $\pm$ 3σ of the mean mass. Add to each of them 2 oppositely-charged pion candidates produced at the same vertex.
- Refit the 5 tracks. Require that the primary vertex [B_c(2S) and B_c production] and secondary vertex [J/ψ production and decay] be separated. Constrain the invariant mass of the $\mu^+\mu^-$ to the J/ψ world average value [exactly 3.0969 GeV]. Require that the B_c momentum point back to the B_c(2S) vertex. If more than one B_c(2S) candidate is reconstructed, take the one with the best χ^2.
- All steps in the analysis are confirmed by applying them to reconstruction of the similar and well-known signal for $B^+ \to J/\psi K^+$.

The new state, at Q = 288 MeV:





- *Signal:* Gaussian. *Background:* 3^{rd}-order polynomial.
- Yield, width, and background shape are consistent across 2011-12.
- Sources of uncertainties on Q: fitting procedure, hadronic momentum scale, ground state mass, vertex quality cut: together, 4.1 MeV
- Significance evaluated with pseudo-experiments is 3.7σ in 2011 and 4.5σ in 2012. For the merged dataset, including the "look elsewhere effect," significance = 5.2σ. The local significance is 5.4σ.
- Absolute mass of the state: $Q + m(B_c) + 2m(\pi)$ is

6842 ± 4(stat) ± 5(syst) MeV.

This is consistent with predictions for the mass and decay chain of the $B_c(2S)$ and so is identified as *the first observation of an excited B_c state.*

A few conclusions…

❖ A new resonance has been observed by the ATLAS experiment at the LHC *(Phys. Rev. Lett. 113, 212004 (2014))* in both the 7 TeV and 8 TeV datasets. It is interpreted as the first observation of an excited state of the B_c meson. This is the heaviest meson with quarks of different flavors.

❖ B_c measurements such as this one are challenging QCD theory and can provide road signs for its future development.

❖ The opportunity to deepen our understanding of the Strong Force has never been better.

❖ There is even more to see at the LHC than the Higgs.

Theoretical references on the B_c family

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